

**Development of a Portable, Ground-based Ozone Lidar Instrument for
Tropospheric Ozone Research and Educational Training**

Final Report

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Submitted to

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Final Report

Introduction: Project Objectives

The objective of this research project is to develop a portable, eye-safe, ground-based ozone lidar instrument specialized for ozone differential absorption lidar (DIAL) measurements in the troposphere. This research project directly supports the goal of NASA's Earth Science Enterprise to understand the distribution and budget of tropospheric ozone (objective 1.5 of the Earth Science Strategic Enterprise Plan, 1998-2002). It can participate in ground validation experiments for TES, a tropospheric ozone satellite mission due to be launched in 2002. It can also be utilized for correlative ground measurements in future GTE (Global Tropospheric Experiment) and space-based ozone lidar missions, such as ORACLE. Multiple ground-based ozone lidar systems would improve the data obtained through current ozone-sonde networks. This prototype instrument could serve as the basic unit for these and other future monitoring projects requiring multi-instrument networks, such as that proposed for the Global Tropospheric Ozone Project (GTOP). GTOP is currently being formulated by a scientific panel of the International Global Atmospheric Chemistry Project to meet its goal to better understand the processes that control the global distribution of tropospheric ozone. In order for the lidar to be widely deployed in networks, it must be fairly easy to use and maintain as well as being cost-competitive with a ground station launching ozonesondes several times a day. A second 2-year grant to continue this effort with students participating in ground tests and system improvements has been awarded by OEOP.

This project also supports existing NASA lidar missions through its development of advanced, compact lidar technology. Innovations in both transmitters and receivers have been made in this project. Finally, this system could be modified in the future to probe more deeply into the stratosphere. This could be accomplished by increasing the emitted energy or optimizing the wavelengths for this purpose.

In addition to NASA, this system has applications to the EPA, NOAA, and the DOD. An AFOSR grant has been awarded based on the results of this effort to fund advanced transmitter development at medium (20-40 mJ) energies. A second proposal to the DOD with a letter of support from Air Force Research Laboratory, has been submitted to extend this uv laser technology to 100 mJ levels. Thus, this project has enabled students and faculty at Hampton University to begin to develop research efforts in support of the mission of the DOD.

This instrument will be based at HU to meet our educational goal to train students in lidar technology as well as atmospheric ozone data analysis and interpretation. It will be also available for off-site measurement campaigns and will serve as a test bed for further instrument development. Later development beyond this grant to extend the scientific usefulness of the instrument may include incorporation of an aerosol channel and upgrading the laser to make stratospheric ozone measurements. Seven undergraduates, three graduate students, and one postdoctoral researcher (formerly an HU student) have been active participants in this research effort.

Technical Approach

To achieve these research goals, emphasis in this project is placed upon the development of (1) all-solid state transmitters which can reliably produce 20-40 mJ pulses in the ultraviolet, (2) a highly efficient, narrow-bandpass receiver, (3) dual analog and photon-counting detector channels, (4) flexible, user-friendly control software, and (5) a mathematical model of the laser transmitter, atmosphere, receiver, and data acquisition system.

This project leverages the significant research accomplishments in the area of lasers and lidar technology by NASA, Hampton University, and ITT Systems and Sciences. Through technical consultations, equipment loans, and cooperative laboratory work at ITT, NASA, and HU, technologies for this project have been selected and tested.

Moreover, this project is a vehicle through which scientists and engineers at the three organizations can cooperate to achieve the educational program goals of MURED. Through this project, Hampton University students have interacted directly with personnel from NASA and ITT to further their training in NASA-related technologies and science.

Research Objectives and Accomplishments

1. Evaluation, selection and testing of laser transmitter technologies

The initial evaluation of candidate lasers was based upon a literature search and technical discussions with industry, university, NASA LaRC, and ITT scientists and engineers. This evaluation reduced the candidates to three: solid state Raman oscillators (SRO's), Optical Parametric oscillators (OPO's), and Titanium-doped sapphire lasers (Ti:S). All of these are pumped by Nd:YAG lasers, are all-solid state, and are reasonably compact and efficient. While uv lasers based upon liquids and gases have been utilized in ozone DIAL systems for many years, these substances are usually awkward to handle, toxic, and require frequent replacement. Sources based on Nd:YAG pump lasers are attractive to NASA for space and airborne applications, since Nd:YAG lasers can themselves be pumped by laser diodes, the most efficient laser pumping technology available. ITT, LaRC and HU scientists had direct experience with excimer, dye, alexandrite, Nd:YLF lasers as well as these three laser systems and lidar systems based on these lasers, and could make a well-informed evaluation from a system point of view and not just a laser engineering point of view.

These three technologies were under theoretical and experimental evaluation by ongoing research programs at HU, ITT, and NASA LaRC. HU has been pursuing SRO technology since 1995, based upon initial experiments at LaRC. LaRC has been developing Ti:S lasers for almost 10 years, and has successfully demonstrated this laser in the LASE (Lidar Atmospheric Sensing Experiment) system, which autonomously measures water vapor from the NASA ER-2 aircraft. ITT has demonstrated a very efficient OPO technology, based upon work done by Caltech.

At the close of the first year of the grant, an evaluation of the current state of these laser technologies was performed which clearly indicated that the OPO laser technology was the optimal choice at the present time. This decision was based upon the laboratory demonstration of adequate laser energy, technical simplicity, compactness, and cost.

However, the development of SRO and Ti:S laser technologies are continuing, and may prove advantageous within a few years.

Our laser development effort to support this system has focused on two approaches: Raman shifting in solid state materials and optical parametric oscillators. The OPO development work has led most quickly to a viable compact transmitter, but the Raman technology will continue because of its demonstrated long-term promise. Both approaches have been fruitful: the OPO laser will be featured in an upcoming *Photonics Spectra* article, while the Raman work being carried out jointly at NASA LaRC has been awarded a \$75k DDF (Director's Discretionary Fund) award (pending NASA's budget in the next fiscal year). In addition, we have been the first to demonstrate Raman laser action in lead tungstate with nanosecond pulses through a collaboration with Dr. Alexander Kaminskii and his Joint Open Laboratory for Laser Crystals and Precise Laser Systems (manuscript in preparation).

The OPO system is shown in figure 1. We mix the output wavelengths of singly resonant IR Type II KTA OPO's with the 355-nm output of a frequency-tripled Nd:YAG laser. The OPO's are pumped by 145mJ of the 1064-nm fundamental wavelength from the injection-seeded Nd:YAG laser and are operated at 1.55 and 1.91 microns. The pump beam diameter is 4 mm. The tripler provides approximately 125 mJ of uv into the mixer. The resulting uv output energy from the mixers have been measured to be approximately 38 mJ for both 289 nm and 299 nm, corresponding to an overall conversion efficiency of 7%. (A typical dye laser system starts with 1.3 J at 1064 nm and produces 60 mJ in the UV— 4.6% efficient) When unseeded, the uv output is approximately 20 mJ. The divergence of the uv output is approximately the same as the 355 nm beam (~1 mrad full angle) and the uv linewidth is under 0.2 nm (instrumentation limited). Prior to transmission from the lidar system, the uv beam will be expanded to be eyesafe. The development of this OPO relied on NASA funding, equipment loans and technical advice from NASA Langley and NASA Goddard, and internal research funding from ITT.

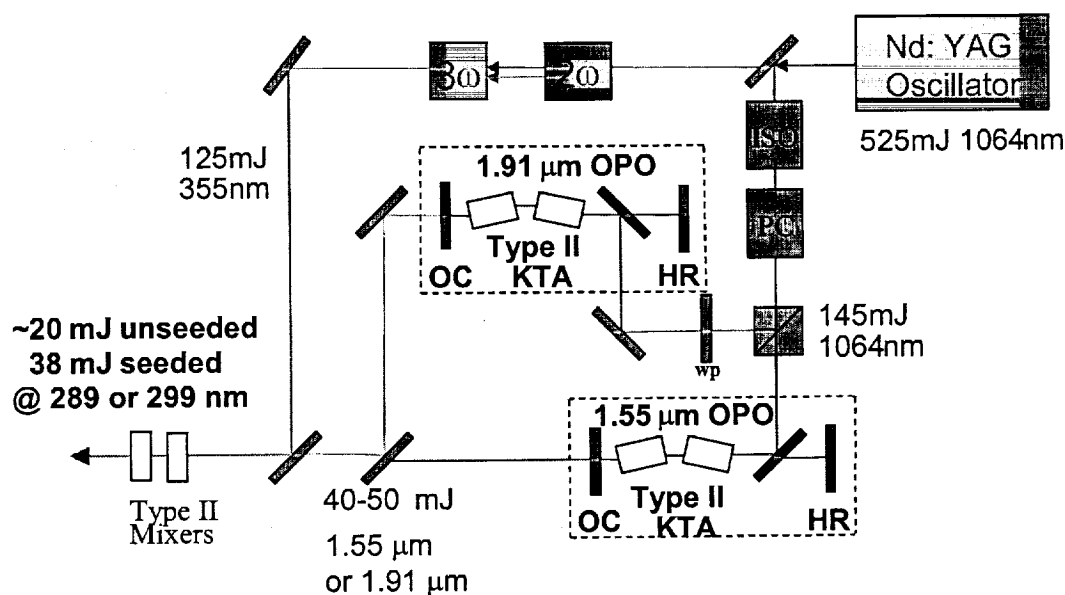


Figure 1. The HU-ITT-NASA OPO

The Raman laser research has emphasized two materials, barium nitrate and lead tungstate. With an Nd:YAG pump source, and one or two Stokes shifts in these materials, plus frequency mixing and doubling, all the key wavelengths needed for ozone DIAL for space-based, ground-based and airborne systems can be accessed: 289 nm, 299 nm, 311 nm, 319 nm. With the addition of iodate crystal Raman shifters, 306 nm can also be obtained. Moreover with this pump source and this set of crystals, every wavelength between 266 and 320 nm can be reached within ± 3 nm with at most two Raman shifts per crystal.

Figure 2 shows the setup and results for a Raman shifting experiment with barium nitrate carried out jointly with NASA LaRC. In this system, an Nd:YAG laser pumps a low power oscillator yielding a low energy seed beam with excellent spatial properties for later amplification. The efficiency of the system from pump to first Stokes is 33%; assuming 25% efficiency for quadrupling to the ultraviolet, the overall efficiency from pump to uv would be 8%. This work will be continued under the awarded \$75k DDF award, pending availability of funds in the next fiscal year.

At Hampton University, we have performed further experiments with barium nitrate oscillators, yielding conversion efficiencies of approximately 45% in oscillator-only configurations. Theoretical equations describing Raman amplifiers have been used to model upcoming oscillator-amplifier experiments.

We have also performed the first demonstration of Raman laser operation with lead tungstate in the nanosecond time regime. Lead tungstate is an attractive material because it is currently commercially produced inexpensively in large quantities for scintillators for CERN. Unlike barium nitrate, very large non-hydroscopic crystals with good optical quality have been grown. The crystals used in our experiments are uncoated and only have a standard (not laser quality) polish. Figure 3 is a plot of conversion efficiency vs. pump power for our oscillator experiments. Given the preliminary nature of this system, the results are very promising. The beam quality coming from this oscillator is suitable for amplifier experiments.

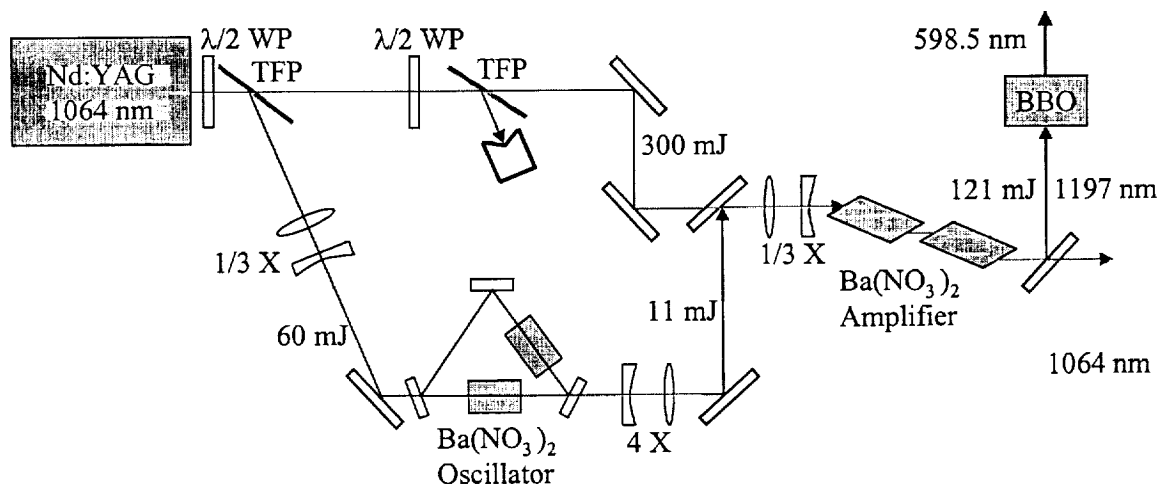


Figure 2. The NASA-HU Barium Nitrate laser system

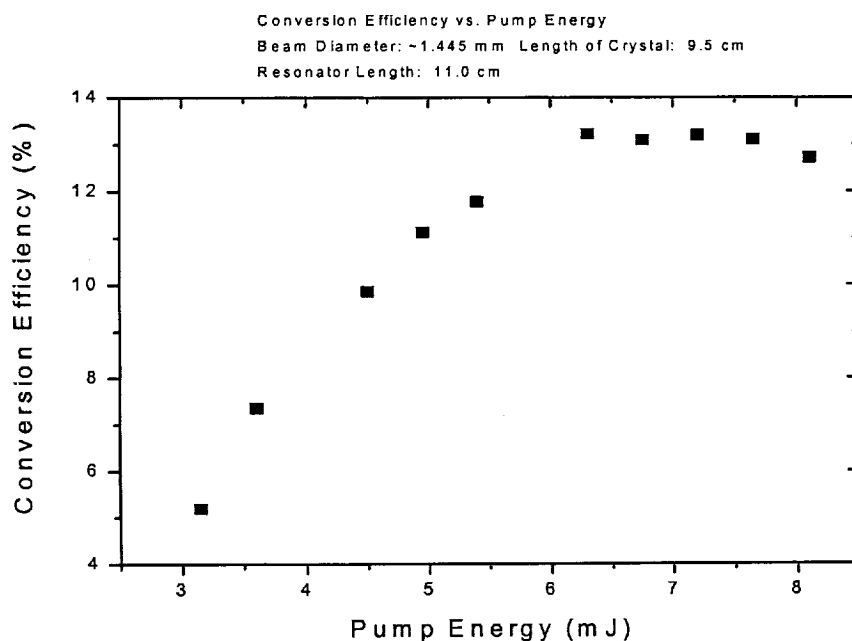


Figure 3. Conversion efficiency in a lead tungstate Raman oscillator

2. Compact Lidar System Structure

One of the primary goals of the project has been to develop a compact, portable system, suitable for field deployment. The ozone lidar system structure, meeting this goal is shown in figure 4. The two HU students, Mika Edmondson (far right) and Kyle Lewis (far left) participated in the testing of this system during their 8-week student internships at ITT during the summer of 1999. The transceiver module, illustrated in figure 5, is also suitable for small aircraft and UAV (Unmanned Aeronautical Vehicle) applications.

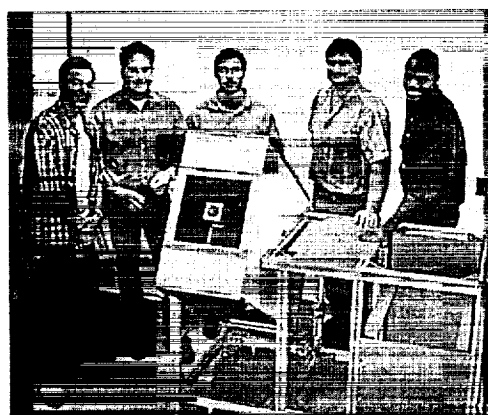


Figure 4: HU students and ITT scientists with the ozone lidar system at ITT

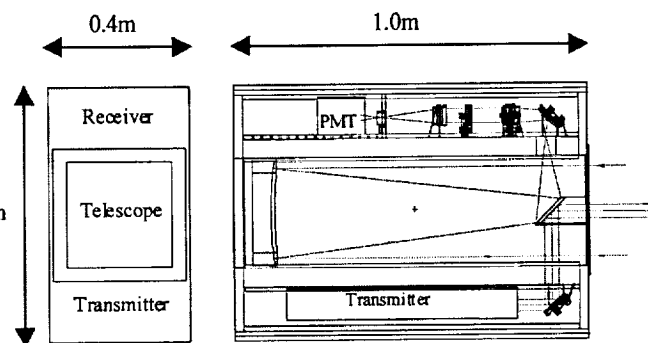


Figure 5: Schematic of the transceiver module.

The fully integrated transmitter and receiver are shown in figures 6 and 7. By rotating the transceiver module, each compartment is easily accessible for modification and maintenance. Figure 8 is a photograph of the complete system prior to integration of the computer data acquisition system.

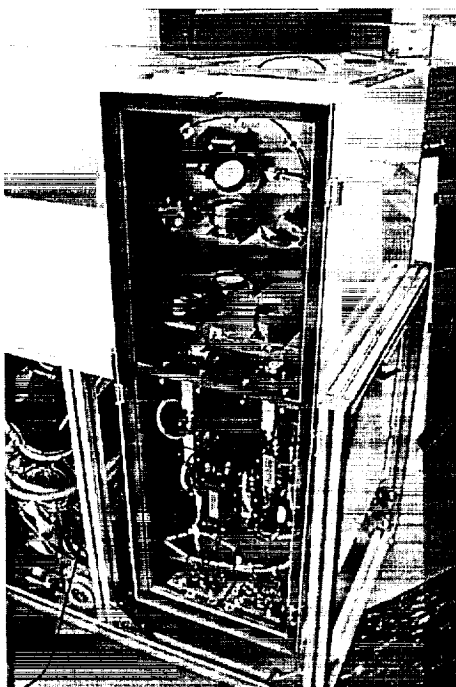


Figure 7. The integrated receiver

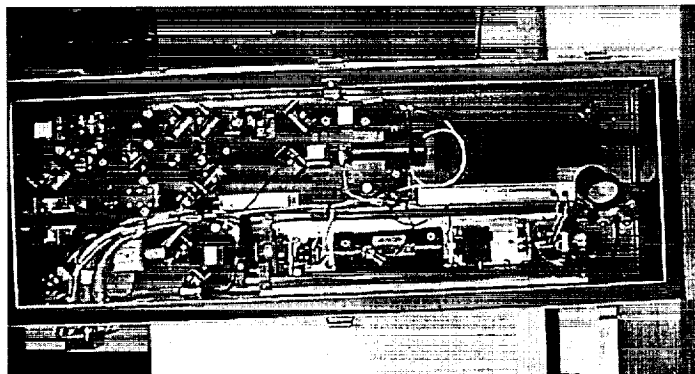


Figure 6. The integrated transmitter

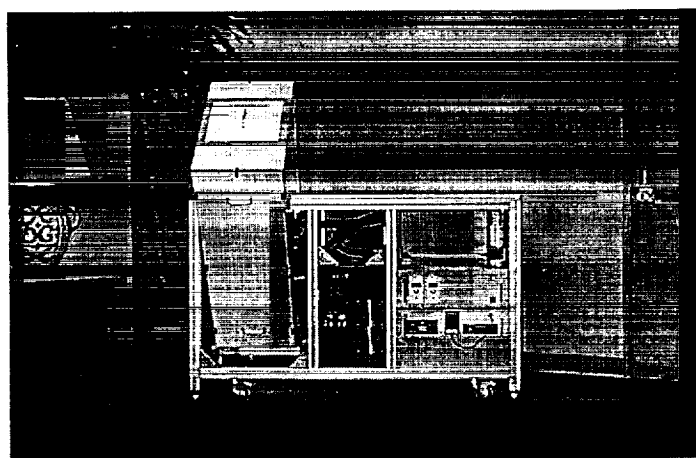


Figure 8. The integrated lidar system structure.

3. Evaluation, selection, modelling and fabrication of the receiver.

ITT designed the lidar receiver based upon technical requirements defined by HU. They evaluated several possibilities and selected a highly-efficient grating-based filtering system with a square, parabolic primary mirror. A raytrace analysis was performed of the complete receiver optical train in order to quantify the resulting bandpass and spotsize for the receiver. The analysis predicted a bandpass of 2.4 nm (FWHM). In the laboratory, this bandpass was measured to be 2.6 nm, in excellent agreement. This work is further discussed in the reprints included in the appendices.

Several innovations in receiver technologies and components have been incorporated in the design and development of the receiver subsystem for the ground-based prototype O₃ DIAL system. Some of the most significant advancements and their impact on system size, weight, cost and performance are listed here (see reprints in appendix for further details):

- Square form factor telescope primary mirror – 30% decrease in receiver volume compared to a round mirror telescope with equivalent collection area and $f/\#$,
- Utilization of both the +1 and –1 orders of the diffraction grating to provide near-field and far-field optical paths – maximize efficiency and flexibility in operational pulse formats,
- Integral telescope, receiver, and transmitter with light-weight carbon fiber structure and light-weight primary mirror – minimize size, weight and thermal misalignment sensitivity,
- High efficiency UV coatings on all optics including diffraction grating – increased throughput by factor of 2.5 over typical current systems,
- Fast (under 1 microsecond) optical shutter technology utilizing a membrane mirror light shutter (MMLS).
- Ultracompact Hamamatsu 7400 series photomultiplier tubes, featuring excellent signal induced bias characteristics and gating capability.

4. Selection and testing of data acquisition system and control software

The data acquisition hardware was chosen and purchased based upon the model calculations which showed that dual A/D detection channels plus a single photon-counting channel are required. LabVIEW was chosen as the system software since it could control a variety of data acquisition boards as well as provide for data analysis and display. Its graphical nature makes it particularly easy to learn and implement. See the appendices for hardware specifications.

5. Development and use of a mathematical model to calculate DIAL system performance and cost-benefit analysis for system design

A complete lidar system computer model was developed, incorporating characteristics of the laser, the atmosphere, the receiver, the data acquisition hardware, and signal averaging. This program was utilized to evaluate the impact of making various technology choices upon the precision of the resulting ozone measurement. In this manner, a cost-benefit analysis could be performed in order to guide the system design so that scientifically useful measurements can be made with the least cost. The parameters utilized in the system model as well as model results are presented in the appendices.

6. Current Status

The lidar instrument is currently at ITT in order to integrate the advanced transmitter funded under the DOD Infrastructure Support Grant. Once this transmitter is integrated, the system will be shipped to HU for ground testing at HU and at Wallops Island, where NASA regularly launches ozonesondes.

Educational Objectives and Accomplishments

1. Training of students in laser remote sensing techniques and atmospheric science

- a. During the 1997-1998 academic year, Roosevelt Elivert (EE) and Brandi Thomas (physics) performed research projects in lidar data acquisition, LabVIEW programming and the importance and chemistry of tropospheric ozone. This led to their presentation at the third annual Hampton University Undergraduate Science Day.

- b. During the summer of 1998, five undergraduates were taught a course in atmospheric science and the remote sensing of ozone using lidar as part of their summer research programs. Three of these students were part of Hampton University's AURORA (Advanced Undergraduate Research Using Optical Radiation in the Atmosphere) summer program in atmospheric science, and one was part of Hampton University's UnIPhy-REU (Undergraduate Institute in Physics-Research Experiences for Undergraduates) program.
- c. Brandi Thomas, Crystal Toppin, and Roosevelt Elivert continued their research projects during the 1998-1999 academic year (Figure 9), leading to another presentation at the 4th HU Undergraduate Science Day. Roosevelt graduated (B.S., EE) in December, 1998 and is employed at Nortel, in Charlottesville, NC. Brandi and Crystal are continuing this research for the 1999-2000 academic year. Crystal has been awarded a Virginia Space Grant Consortium scholarship to continue her research during this period.
- d. As part of their summer research, three undergraduates attended the 19th International Laser Radar Conference in Annapolis, Md., along with other Hampton University graduate students and faculty. This premier international conference, rarely in the US, provided the students with a taste of atmospheric lidar research projects ongoing throughout the world. Numerous papers were presented on ozone lidar measurements, enabling them to place their work in a worldwide professional context
- e. The success of this program, coupled with research ongoing in RCOP at HU and the Center for Atmospheric Sciences at HU, with the support of ITT and NASA Langley has led to the establishment of the Center for Lidar and Atmospheric Sciences Students (CLASS) at Hampton University.
- f. During the summer of 1999, two CLASS students, Mika Edmondson and Kyle Lewis, were trained in lidar technologies at ITT Industries Albuquerque. Their training included the development, analysis and testing of this lidar system (Figure 10).
- g. A new Ph.D. student, Ms. Renee Payne, will be performing experiments with the lidar system for her Ph.D. thesis project.

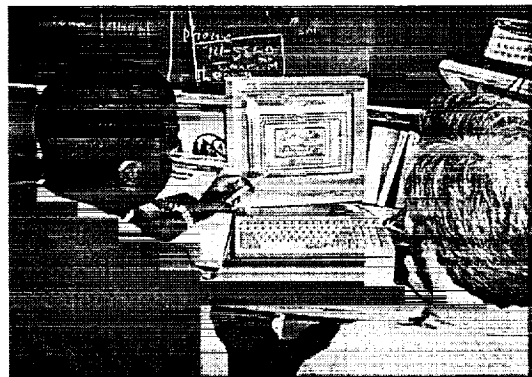


Figure 9. Mr. Roosevelt Elivert, senior EE major, discusses his LabVIEW program with Dr. Thomas Zenker.



Figure 10. HU student interns Mika Edmondson and Kyle Lewis assist ITT engineer Dale Richter with the testing of the ozone lidar system.

2. Training of students in laser physics

- a. Mr. Christophe McCray, Ph.D. candidate, has been performing theoretical and experimental research on stimulated Raman scattering as a means to produce the ultraviolet laser energy needed for the lidar project (Fig. 11). The results of his work have been presented at conferences and have been accepted for publication. In addition to working with faculty and postdocs at Hampton University, he has consulted with Mr. Waverly Marsh at NASA Langley Research Center, Dr. Karl Koch of Phillips Air Force Laboratory (Albuquerque—now at Corning), and Dr. Alexander Kaminskii, Visiting Distinguished Research Professor from Moscow State University on theoretical and experimental aspects of the physics of Raman lasers.
- b. As part of the AURORA and UniPhy programs, the students involved in this project through those summer programs were taught a short course in laser physics and its application to optical remote sensing.



Figure 11. Mr. Christophe McCray, Ph.D. candidate, develops a Raman laser for the ozone DIAL project.

3. Integration with other Hampton University Outreach Programs

As mentioned, this project has provided research topics for HU's AURORA and UniPhy summer programs, and provides an ozone lidar instrument to complement the aerosol lidar system being designed and constructed by CLASS students. When completed, the ozone instrument will also be utilized as part of the CLASS outreach program to high school and middle schools.

Future Improvements and Applications

Beyond the performance period of this grant, additional sources of funding will be sought to further test and improve the lidar instrument and to employ it in field campaigns sponsored by NASA or other agencies such as NOAA and the EPA. These agencies have already expressed interest in portable ozone lidar systems such as this one. System improvements may include increasing the range of the system to probe the stratospheric ozone layer and the inclusion of an aerosol channel to simultaneously measure atmospheric structure and particle loading.

This instrument would be a valuable addition to the CLASS program at Hampton University. If funds through CLASS can be identified to support students to be trained to use this system, then a very powerful synergy would result between the scanning aerosol instrument built under CLASS and the ozone lidar. The CLASS instrument would enable the evolution of the atmospheric structure, particle loading, and transport to be studied in 3-D to provide an atmospheric context for the 1-dimensional ozone measurements possible with the ozone instrument. Eventually, the scanning technology developed for CLASS could be evaluated for use in the ozone lidar system.

Hampton University students will actively participate in these system improvements and field deployments. Engineers at ITT Systems and Sciences have expressed their desire to assist HU in obtaining further funding to jointly pursue these endeavors, and has offered to host HU students and faculty for joint research at ITT provided sources of funding to support student travel can be identified. ITT will be hosting students for the CLASS project in forthcoming summers.

Leveraged Funding: Grants Proposed and Awarded

In addition to making a valuable contribution to the success of the Research Center for Optical Physics (RCOP), and to providing basis of the HU-NASA-ITT collaboration on lidar research which has led to the CLASS project, several grants have directly resulted from this collaboration and will be used to continue this effort:

Research Grants:

PI: Dr. Thomas Chyba
 Title: "Student Field Testing of the HU Compact Ozone Lidar System"
 Dates: 7-1-99 to 6-30-01
 Agency: NASA MURED (Langley Research Center)
 Total \$200,000

PI: Dr. Thomas Chyba
 Title: "Tunable ultraviolet and infrared laser source for student lidar experiments"
 Dates: 7-1-99 to 6-30-00
 Agency: AFOSR
 Total \$185,000

Educational (Student Support) Grants:

The following grants and fellowships have been awarded to support students:

PI: Dr. Thomas Chyba
 Title: "Summer Industrial Internship at ITT"
 Dates: 6-1-99 to 7-31-99
 Agency: Virginia Space Grant Consortium
 Total: \$8,000

PI: Ms. Renee Payne-Baggot (graduate student)
 Title: ONR Graduate Fellowship
 Agency: Office of Naval Research (ONR)
 Amount: \$18,000/year

PI: Ms. Renee Payne-Baggot (graduate student)
 Title: VSGC Graduate Fellowship
 Agency: Virginia Space Grant Consortium (VSGC)
 Amount: \$4,000/year

PI: Mr. Christophe McCray (graduate student)
 Title: VSGC Graduate Fellowship
 Agency: Virginia Space Grant Consortium (VSGC)
 Amount: \$4,000/year

PI: Ms. Crystal Toppin (undergraduate student)
 Title: VSGC Undergraduate Scholarship
 Agency: Virginia Space Grant Consortium (VSGC)
 Amount: \$4,000/year

Pending Grants:

These proposals build upon this research effort and broaden its scope:

PI: Dr. George Papen, University of Illinois
 Co-I: Dr. Thomas Chyba (in addition to many others)
 Title: "Center for Atmospheric Sensor Systems Engineering"
 Dates: 4-1-00 to 3-31-04
 Agency: NSF
 Total: \$10,000,000

PI: Dr. Thomas Chyba
 Title: High Peak Power Tunable Laser for Remote Detection of Bioagent Clouds
 Dates: 3-31-00 to 3-30-01
 Agency: AFOSR
 Total: \$385,000

Leveraged Funding: Equipment loans, in-kind support, and matching funds

NASA LaRC (J. Barnes) \$50k in equipment loans
 NASA Goddard (T. McGee) \$35k in equipment loans
 ITT Industries, Systems Division (N. S. Higdon) \$50k in Internal Research & Development funds, \$30k in-kind contribution for student internship support

Presentations by Students (student names in boldface)

1. **Thomas, B., R. Elivert**, T. Zenker, and T. H. Chyba, "A data acquisition system for lidar measurements of ozone", Hampton University Third Annual Student Research Symposium, February 13-14, 1998.
2. **McCray, C. L.** and T. H. Chyba, "Stimulated Raman Amplification, Oscillation, and Linewidth Measurements in Barium Nitrate", NASA University Research Center Technical Conference, February 22-25, 1998, paper MLM2-4.

3. **McCray, C. L.**, and T. H. Chyba, "Measurements of Stimulated Raman Amplification and Oscillation in Barium Nitrate", Advanced Solid State Lasers 1998, February 2-4, 1998, paper AME10.
4. **Larson, D.**, T. Zenker, and T. H. Chyba, "LabVIEW Ozone Display Program", Hampton University Advanced Undergraduate Research Using Optical Radiation in the Atmosphere Research Day, July 24, 1998.
5. **Toppin, C.**, T. Zenker, and T. H. Chyba, "Ozone Altitude Profile Error Analysis for Ozone Lidar Project", Hampton University Advanced Undergraduate Research Using Optical Radiation in the Atmosphere Research Day, July 24, 1998.
6. **Thomas, B.**, T. Zenker, and T. H. Chyba, "Ozone Altitude Profile Data Analysis for the Ozone Lidar Project", Hampton University Advanced Undergraduate Research Using Optical Radiation in the Atmosphere Research Day, July 24, 1998.
7. **McNeil, J.**, T. Zenker, and T. H. Chyba, "Development of a Computerized Energy Monitor for an OPO-Based Lidar System" Hampton University Undergraduate Institute in Physics-Research Experiences for Undergraduates Research Day, July 23, 1998.
8. **Thomas, B., C. Toppin**, T. Zenker, and T. H. Chyba, "Ozone Altitude Profile Analysis for the Ozone Lidar Project", Hampton University Fourth Annual Student Research Symposium, Hampton University, Feb. 12-13, 1999.

Presentations by Faculty

1. Chyba, T. H., T. Zenker, **C. L. McCray**, H. R. Lee, **B. Thomas, R. Elivert**, N. S. Higdon, D. A. Richter, and J. Fishman, "Development of a compact ground-based ozone DIAL system", 19th International Laser Radar Conference, July 6-10, 1998, paper PS3.2-9
2. Zenker, T., T. H. Chyba, J. Fishman, N. S. Higdon, and D. A. Richter, "A compact ground-based uv lidar system for a global tropospheric ozone network", 1998 Symposium of the Commission on Atmospheric Chemistry and Global Pollution (CACGP) and the International Global Atmospheric Chemistry Project (IGAC), August 19-25, 1998.
3. Chyba, T. H., T. Zenker, **C. L. McCray**, H. R. Lee, **B. Thomas, R. Elivert**, N. S. Higdon, D. A. Richter, and J. Fishman, "A compact ground-based differential absorption lidar for measurements of tropospheric ozone", 1998 OSA Annual Meeting, October 4-9, 1998, paper WDD22.
4. Zenker, T., Chyba, T. H., **C. L. McCray**, H. R. Lee, **B. Thomas, R. Elivert, C. Toppin, D. Larson**, N. S. Higdon, D. A. Richter, and J. Fishman, "A compact, ground-based uv DIAL system for measurements of tropospheric ozone", SPIE

Symposium, Laser Radar Technology and Applications IV, Orlando, Fl., 5-9 April, 1999, paper 3707-70.

5. Chyba, T. H., T. Zenker, **C. L. McCray**, H. R. Lee, **R. Elivert**, **B. Thomas**, **C. Toppin**, and **D. Larson**, N. S. Higdon, and D. A. Richter, and J. Fishman, "Measurements of tropospheric ozone with a compact uv DIAL system", SPIE Symposium, Application of Lidar to Current Atmospheric Topics III, Denver Colorado, July 23-28, 1999, paper 3757-10.
6. Chyba, T. H., T. Zenker, **C. L. McCray**, H. R. Lee, **R. Elivert**, **B. Thomas**, **C. Toppin**, and **D. Larson**, N. S. Higdon, and D. A. Richter, and J. Fishman, "A compact uv ozone DIAL system", OSA Topical Meeting on Optical Remote Sensing of the Atmosphere, Santa Barbara, California, June 22-24, 1999, paper RTUC5.
7. Chyba, T. H., T. Zenker, **C. L. McCray**, H. R. Lee, **R. Elivert**, **B. Thomas**, **C. Toppin**, and **D. Larson**, N. S. Higdon, and D. A. Richter, and J. Fishman, "Tests of a compact lidar for global monitoring of tropospheric ozone", SPIE Symposium, Environmental Monitoring and Remediation Technologies II, Boston Massachusetts, September 19-22, 1999, paper 3853-13.
8. Chyba, T. H., T. Zenker, N. S. Higdon, D. A. Richter, and J. Fishman, "Status of the development of a Low-cost differential absorption lidar system for tropospheric ozone studies", Sixth Scientific Conference of the International Global Atmospheric Chemistry Project (IGAC), September 13-17, Bologna, Italy.
9. Lee, H. R., **C. L. McCray**, and T. H. Chyba, "Birefringence compensation in a barium nitrate Raman laser" Conference on Lasers and Electro-Optics/Pacific Rim, August 30- September 3, 1999, Seoul, Korea, paper ThG4.
10. Lee, H. R., W. D. Marsh, "On site investigation of Raman oscillator/amplifier", NASA Laser Systems Branch 1999 External Peer Review, August 11, 1999.

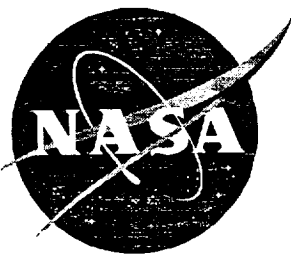
Publications

1. **McCray, C. L.** and T. H. Chyba, "High Resolution Spectral Measurements of Raman Shifts in Barium Nitrate," Optical Materials, 11, 383-390, 1999.
2. **McCray, C. L.** and T. H. Chyba, "Measurements of stimulated Raman amplification and oscillation in barium nitrate," in Advanced Solid State Lasers, Technical Digest (Optical Society of America, Washington, D.C., 1998), pp. 139-141.
3. **McCray, C. L.**, S. W. Lee, and T. H. Chyba, "Measurements of stimulated Raman amplification and Raman shifts in barium nitrate", OSA Trends in Optics and Photonics Vol. 19, Advanced Solid State Lasers, W. Bosenberg and M. M. Fejer, eds. (Optical Society of America, Washington, DC 1998), pp. 550-554.

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Appendix 1. Copy of the article published in the Proceedings of the 19th ILRC.

Appendix 2. Copy of the article published in the Proceedings of the SPIE, Vol. 3757.



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Development of a Compact, Ground-Based Ozone DIAL System

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1. Introduction

We are developing a portable, eye-safe, ground-based ozone lidar instrument specialized for ozone differential absorption lidar (DIAL) measurements in the troposphere. This prototype instrument is intended to operate at remote field sites and to serve as the basic unit for future monitoring projects requiring multi-instrument networks, such as that proposed for the Global Tropospheric Ozone Project (GTOP). GTOP is currently being formulated by a scientific panel of the International Global Atmospheric Chemistry Project to meet its goal to better understand the processes that control the global distribution of tropospheric ozone [1]. In order for the lidar to be widely deployed in networks, it must be fairly easy to use and maintain as well as being cost-competitive with a ground station launching ozone sondes several times a day.

To achieve these goals, emphasis is placed upon the incorporation of (1) all-solid state transmitters which can reliably produce 20-40 mJ pulses, (2) a highly efficient, narrow-bandpass receiver, (3) dual analog and photon-counting detector channels, and (4) flexible, user-friendly control software.

2. Transmitter

Two candidate lasers are currently being evaluated as possible transmitters. Both are based upon mature Nd:YAG laser technology coupled with nonlinear frequency conversion chains to produce the wavelengths needed for differential absorption lidar measurements.

The first approach is based upon Raman shifting in solid-state crystals. It has the advantage of being very efficient and of producing well-defined wavelengths. However, the specific wavelengths produced are dictated by the Raman crystals utilized, so for compact systems this technique restricts the choice of wavelengths to two or three. The use of three wavelengths facilitates some optimization for the particular ozone distribution to be measured. Raman shifting a doubled Nd:YAG laser in an external cavity using barium nitrate and subsequent frequency doubling or mixing to the uv can produce 281.7 and 299.4 nm wavelengths. With a lithium iodate crystal, 289.8 and 303.3 nm pulses can be produced.

Figure 1 illustrates a 2-wavelength uv laser transmitter based upon Raman shifting in barium nitrate. The doubled output from a Q-switched Nd:YAG laser is split into two beams. One beam is mode-matched to a Raman oscillator and pumps it to produce a Raman-shifted output pulse at 599 nm. Residual energies at 563 nm (from the first Stokes shift) and at 532 nm are separated out with a dichroic mirror. The polarization of the 599 nm pulse is then rotated 90° by a Pockels cell and passes through a polarizing beam splitter. Its polarization is then rotated back and its wavelength is frequency doubled to 299 nm, producing the off-line pulse. To produce the on-line pulse, a timing circuit triggers the Pockels cell so that every other Raman pulse is not rotated in polarization. This unrotated pulse is reflected by the polarizing beam splitter. It is frequency-mixed with a portion of the 532 nm pump energy to generate the 282 nm pulse.

Our preliminary work with barium nitrate has demonstrated Raman conversion efficiencies exceeding 45% in the visible with a multimode pump [2]. Both off-line and on-line uv pulses have been produced in our laboratory, but with under 1 mJ pulse energies [3]. The low conversion efficiencies in the uv are due to a combination of high beam divergence from the Raman oscillator and low Raman oscillator energies. In the conference paper, we will present our current results with our redesigned oscillator and oscillator-amplifier configuration.

The alternative transmitter under laboratory evaluation is a Nd:YAG-pumped Type II optical parametric oscillator (OPO) frequency-doubled to the uv [4]. This laser has recently been reported to produce ~10 mJ pulses in the 300-nm region when pumped by 135 mJ of tripled output from an injection-seeded Nd:YAG. It has the advantage of tunability throughout the uv and can therefore be precisely wavelength optimized for a given ozone distribution. However, this also requires computer monitoring and control of the laser wavelength. It also increases the complexity of the wavelength masks in the focal plane of the receiver grating. In addition,

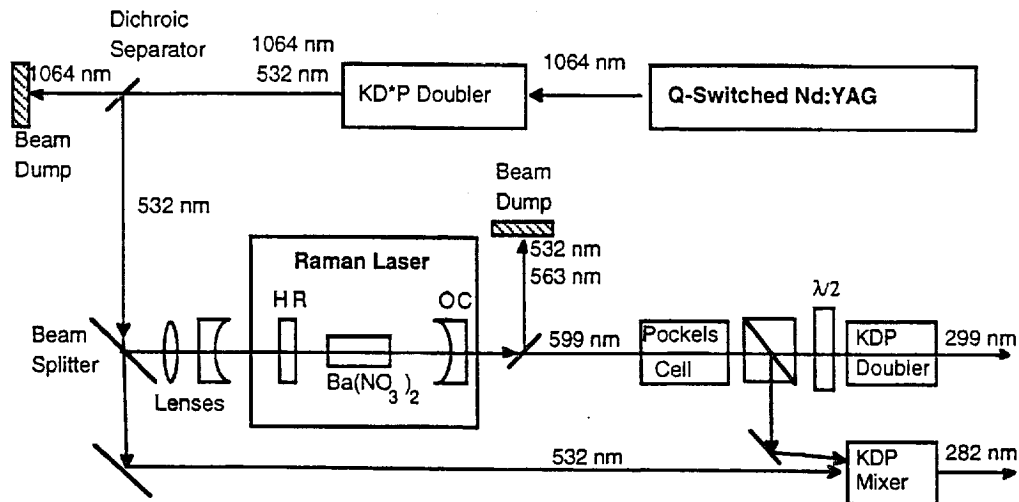


Figure 1. A candidate uv transmitter based upon a barium nitrate Raman oscillator

the injection-seeded pump laser increases the cost and complexity of the transmitter. Results for this laser will be presented in the conference paper.

3. Receiver

The lidar receiver utilizes a 12" square parabolic primary mirror and a grating-based spectrometer as a wavelength filter (Figure 2). Daylight prefiltering is performed by reflective dielectric coatings on the fold mirrors before the grating. For stock commercial triplet lenses and gratings, the bandpass in the focal plane of the grating is computed to be 2.4 nm for a single wavelength channel. By opening a shutter in the focal plane of the grating to allow through only the transmitted wavelength, the bandwidth can be maintained at 2.4 nm for a multi-wavelength system. With commercially available dielectric coatings, the throughput efficiency from the atmosphere to the detector plane is calculated to be ~60% for the far field (photon-counting mode) channel. The near-field (analog-mode) channel (not shown) will utilize the negative first order reflection from the grating and not reduce the efficiency of the far-field channel. A number of techniques are under investigation to address the problem of detector saturation and signal-induced bias due to the strong near field return.

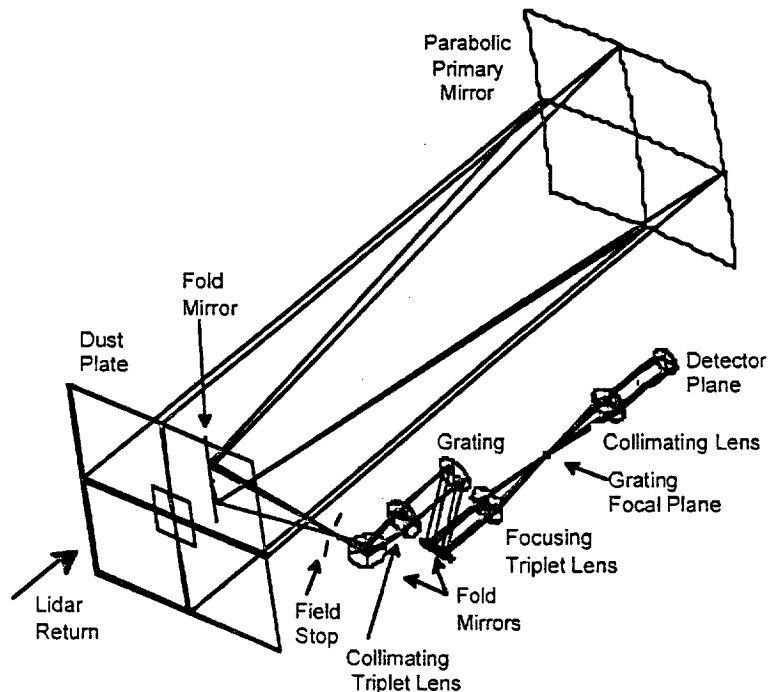


Figure 2. The lidar receiver optical layout.

Lightweight, graphite epoxy breadboards form the four walls of the telescope. The receiver and transmitter optics can be directly attached to two of these breadboards, making the entire system extremely compact.

The data acquisition system consists of a field-hardened personal computer with a 12-bit A/D and 300 MHz counter cards. Beam steering, system timing, and the monitoring of output pulse energies will also be computer controlled. The control and data analysis software is being written in LabVIEW.

4. Calculated Ozone DIAL performance

We have calculated the expected DIAL performance for our receiver and transmitter characteristics. As an example, we choose an ozone profile measured at the tropical ozone sonde station in Brazzaville, Congo, on day 294 in 1992 [5]. Using these data we simulate lidar return signals [6] accounting for Rayleigh scattering and extinction due to Rayleigh scattering and ozone absorption [7] for our chosen on- and off-line wavelength pairs: 281.7/299.4 nm and 289.8/303.3 nm for the Nd:YAG Raman transmitters and 286/299.4 nm for the Nd:YAG OPO-based system. The signal to noise (S/N) ratios for the DIAL return signal are calculated incorporating the contributions of several error sources: signal noise, sky background radiation for a sun zenith angle of 30° , dark current/counts of the photomultiplier tube (PMT), analog-to-digital resolution (10 usable bits for the analog mode), and the dead time error arising in the photon counting mode at high count rates. Figure 3 depicts the given ozone sonde profile and the calculated total S/N ratios of the far field (photon counting (PC)) channel and for two near field (analog) channels with different sets of operational parameters (A#1, A#2). Key parameters used for the calculations are listed in Table 1.

The S/N ratios shown in Figure 3 stay above ~ 10 for the shorter transmitter wavelength pairs over the entire tropospheric ozone profile, while S/N ratios drop below 10 for the 282/299 nm pair above an altitude of ~ 13 km. The latter pair shows a significantly higher sensitivity for the lower tropospheric ozone but becomes more insensitive for the upper free tropospheric ozone compared to the longer wavelength pairs.

The S/N ratio of the PC channel is primarily limited by signal noise, except above ~ 20 km and below ~ 8 km, where it is limited by dark count shot noise and dead time uncertainty, respectively. Below ~ 6.5 km the maximum anode current of the PMT is exceeded.

The analog channel A#2 shows sufficient overlap with the PC channel at reasonable S/N ratios but the measurements do not extend below ~ 1.8 km because the maximum allowed cathode current of the PMT is exceeded for reasonable PMT gain and ADC range settings. To allow lidar measurements down to 100 m, another analog channel (A#1) whose optical throughput is reduced by a factor of 5 relative to A#2 is needed. Two possible methods to cover the entire altitude range below 7 km with analog channels are: (1) operate two PMTs with a 20/80 beam splitter, or (2) record the lidar return alternately with 20% transmission and full

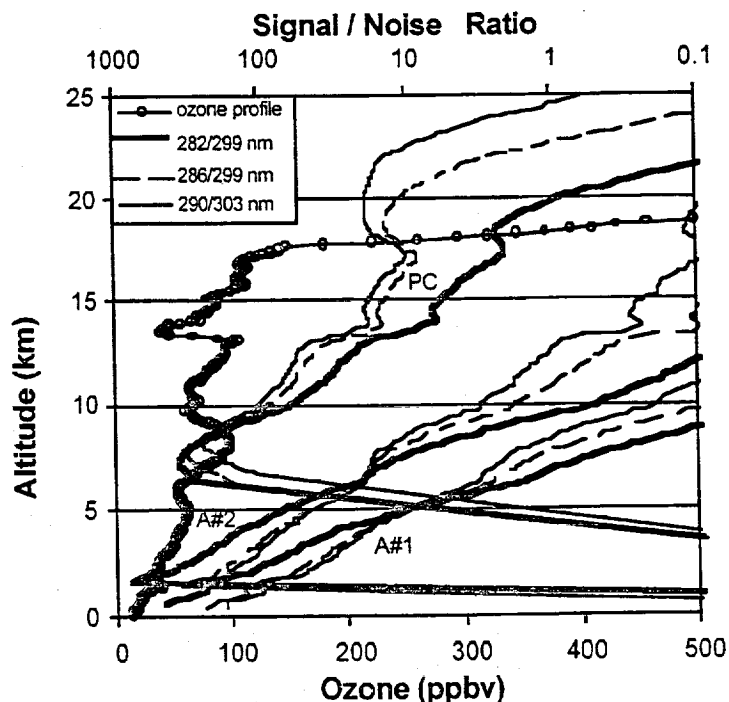


Figure 3. Simulated S/N ratios for the DIAL return computed for the plotted ozone sonde profile.

Table 1. Key parameters for the simulation of DIAL performance.

Transmitter	Transmitted energy, on/off-line Divergence, full angle	30/10 mJ 0.8 mrad
Receiver	Effective telescope area / diameter Total throughput PC channel (grating, order 1) Analog channel (grating, order -1) A#1 A#2 Field of view, full angle Bandpass for each wavelength	0.091 m ² / 13.4" 58.9% 0.29% 1.44% 1 mrad 2.4 nm
Photomultiplier Tubes	Hamamatsu H5600-6 series [8], Quantum efficiency Collection efficiency Rise time Dark anode current/count rate	~ 18% ~ 65% 0.65ns 0.5 nA/80 cnts/s
Range and time resolution	Photon counting channel Analog channel (A#1/A#2) # of pulses averaged, on- or off-line	1000 m 300/500 m 9000*

*this corresponds to a 30/10 min integration for a 10/30 Hz single-wavelength transmitter system.

sensitivity. The S/N ratios of the analog channels are limited by signal noise for S/N greater than ~5 and by dark current or ADC resolution for S/N lower than ~5.

For the system parameters in Table 1, shot noise due to sky background radiation is not expected to limit the lidar performance. In our calculations, a minimum constant background level on the PMT's is assumed for wavelengths shorter than 295 nm, corresponding to the apparent sky background for measurements taken at 295nm with a 2.4 nm optical bandwidth. The value of this minimum level is 10^{-6} W/m²/sr/nm, as measured with a typical telescope setup by Maeda *et al.* [9].

5. Summary

We are developing transmitter, receiver, and data acquisition technologies for a compact, ground-based ozone lidar system. An efficient, narrow-band receiver reduces the energies required for the laser transmitter to meet the measurement S/N objectives. Candidate laser transmitters are currently under evaluation. The current status of the system will be presented in the conference paper.

Acknowledgments

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Measurements of tropospheric ozone with a compact uv DIAL system

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ABSTRACT

Current results from laboratory testing of an eye-safe, ground-based ozone lidar instrument specialized for ozone differential absorption lidar (DIAL) measurements in the troposphere are presented. This compact prototype instrument is intended to be a prototype for operation at remote field sites and to serve as the basic unit for future monitoring projects requiring multi-instrument networks. In order for the lidar to be widely deployed, it must be fairly easy to use and maintain as well as being cost-competitive with a ground station launching ozone sondes several times a week. To achieve these goals, the system incorporates (1) an all-solid state compact OPO transmitter, (2) a highly efficient, narrow bandpass grating-based receiver, (3) dual analog and photon-counting detector channels, and (4) a PC-based data acquisition system.

Keywords: DIAL, lidar, tropospheric ozone

1. INTRODUCTION

A portable, eye-safe, ground-based prototype instrument specialized for ozone differential absorption lidar (DIAL) measurements is currently being tested. The prototype instrument is intended to operate at remote field sites and to serve as the basic unit for future monitoring projects requiring multi-instrument networks, such as that proposed for the Global Tropospheric Ozone Project (GTOP). GTOP is currently being formulated by a scientific panel of the International Global Atmospheric Chemistry Project to meet its goal to better understand the processes that control the global distribution of tropospheric ozone.¹ In order for the lidar to be widely deployed in networks, it must be fairly easy to use and maintain as well as being cost-competitive with alternative technologies. To achieve these goals, the system incorporates (1) a compact all-solid state transmitter, (2) a highly efficient, narrow-bandpass grating-based receiver, (3) dual analog and photon-counting detector channels, and (4) flexible, user-friendly control software.

2. LIDAR SYSTEM STRUCTURE

One major objective of this project is to develop a differential absorption lidar which is compact and portable. Figure 1 is a photograph of the system structure. The structure supports the transceiver box, the laser power supply, its water to air heat exchanger, electronics and the data acquisition computer. The transceiver box is a lightweight carbon fiber structure. It can be manually pivoted and locked to vary the pointing direction. The telescope optics are located in the central compartment of the transceiver box, the laser transmitter is fully integrated in one of its two side compartments and the filtering optics and detectors are in the other one (Figure 2). The transceiver can be oriented horizontal with either side facing up for ease of maintenance.

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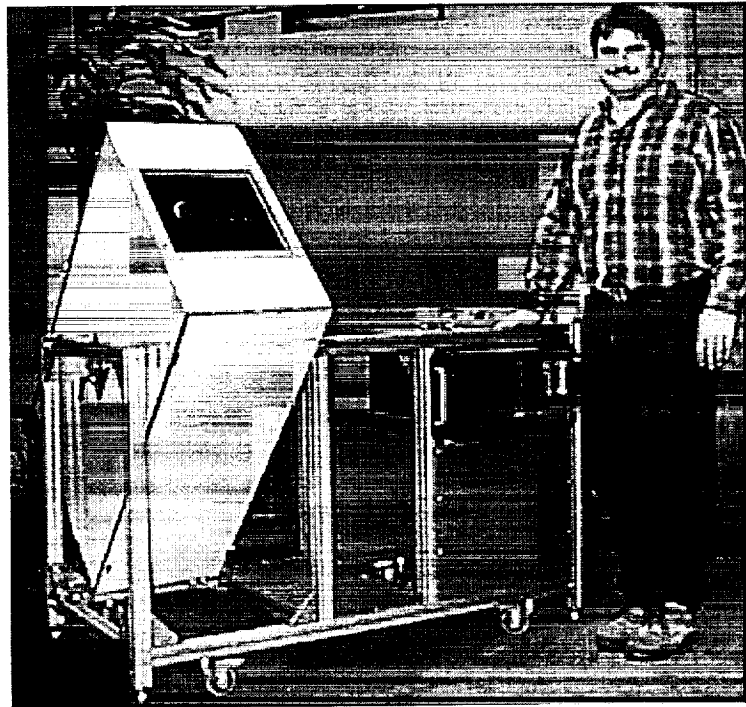


Figure 1: Photograph of the integrated system structure with the transceiver module.

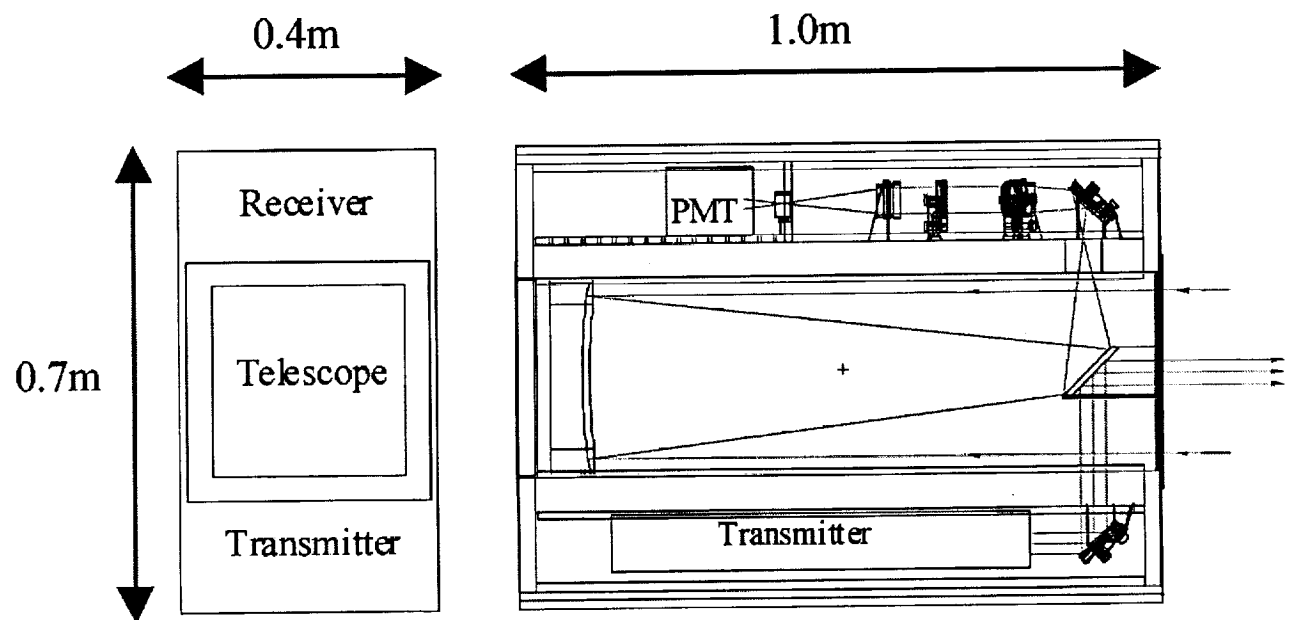


Figure 2: Schematic of the transceiver module.

3. LASER TRANSMITTER

We have previously reported our initial development of a compact solid-state laser source based upon stimulated Raman scattering in barium nitrate,² upon mixing 355-nm radiation with the output of a near-infrared OPO³ and upon frequency-doubling a visible-wavelength Type II BBO OPO.^{3,4} The experimental setup for the Type II BBO OPO is shown in Figure 3. An injection-seeded Nd:YAG laser produces 600 mJ which is frequency-tripled to provide 175 mJ at 355 nm to pump the OPO. We have produced 20 mJ pulses at 299 nm by frequency-doubling the 70 mJ output of the OPO. The linewidth of the uv output was below the resolution of our spectrometer, which is 0.2 nm. When the same OPO is pumped with the pump laser operating in a non-injection-seeded mode, only 10 mJ of uv energy results. The temporal pulse lengths of the unseeded and seeded pump laser are 6 ns and 8 ns, respectively, and the corresponding OPO pulse lengths are 5.5 ns and 6.5 ns. While this system produces sufficient energy for our system, it has several disadvantages, notably its need for a fairly large injection-seeded pump laser and that the OPO must be directly pumped in the uv with substantial pump pulse energies. Since the pump beam is reflected back out of the OPO towards the tripler, the output face of the tripler is damage-prone. Optical isolators operating at 355 nm are available, but optical throughputs are only ~80%. Without an isolator, if the pump beam is pointed at a slight angle to prevent a direct back reflection, the OPO tends to operate at two wavelengths simultaneously.

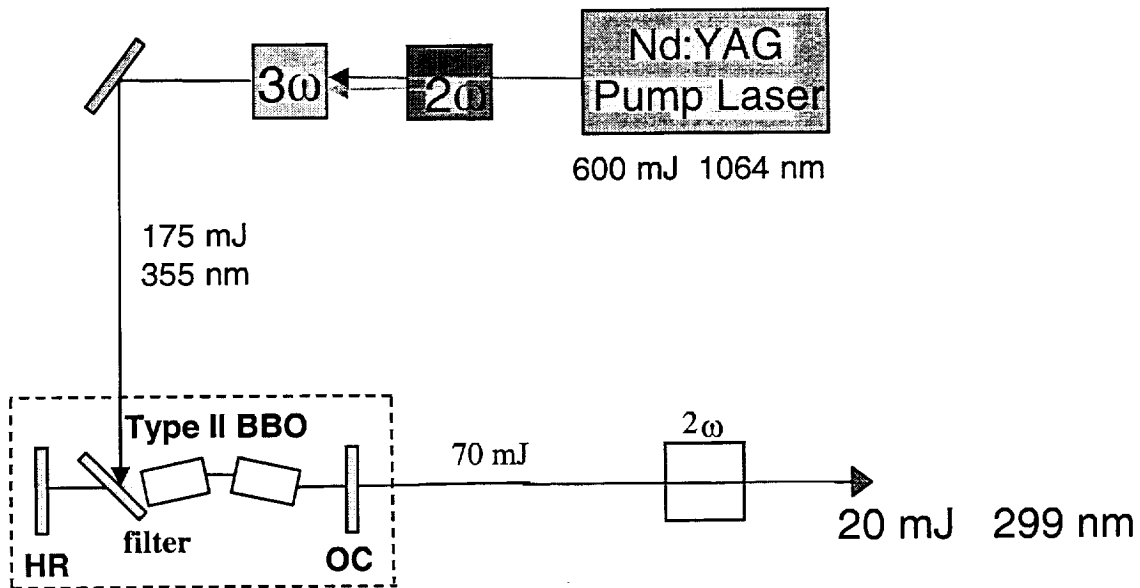


Figure 3. The 355 nm-pumped Type II OPO

We are presently concluding a series of experiments in which we mix the output wavelengths of singly resonant IR Type II KTA OPO's with the 355-nm output of a frequency-tripled Nd:YAG laser. This experimental setup is shown in Figure 3. The OPO's are pumped by 145 mJ of the 1064-nm fundamental wavelength from the injection-seeded Nd:YAG laser and are operated at 1.55 and 1.91 microns. The pump beam diameter is 4 mm. The tripler provides approximately 125 mJ of uv into the mixer. The resulting uv output energy from the mixers have been measured to be approximately 38 mJ for both 289 nm and 299 nm. When unseeded, the uv output is approximately 20 mJ. The divergence of the uv output is approximately the same as the 355 nm beam (~1 mrad full angle) and the uv linewidth is under 0.2 nm (instrumentation limited). These experiments were performed with a large-frame laser which will not fit in the transceiver module. In the conference paper, we will present the results obtained using a custom small-frame injection seeded laser which will fit into transceiver module. Prior to transmission, the uv beam will be expanded to be eyesafe. This is the OPO configuration that will be used as the transmitter for the prototype O₃ DIAL instrument.

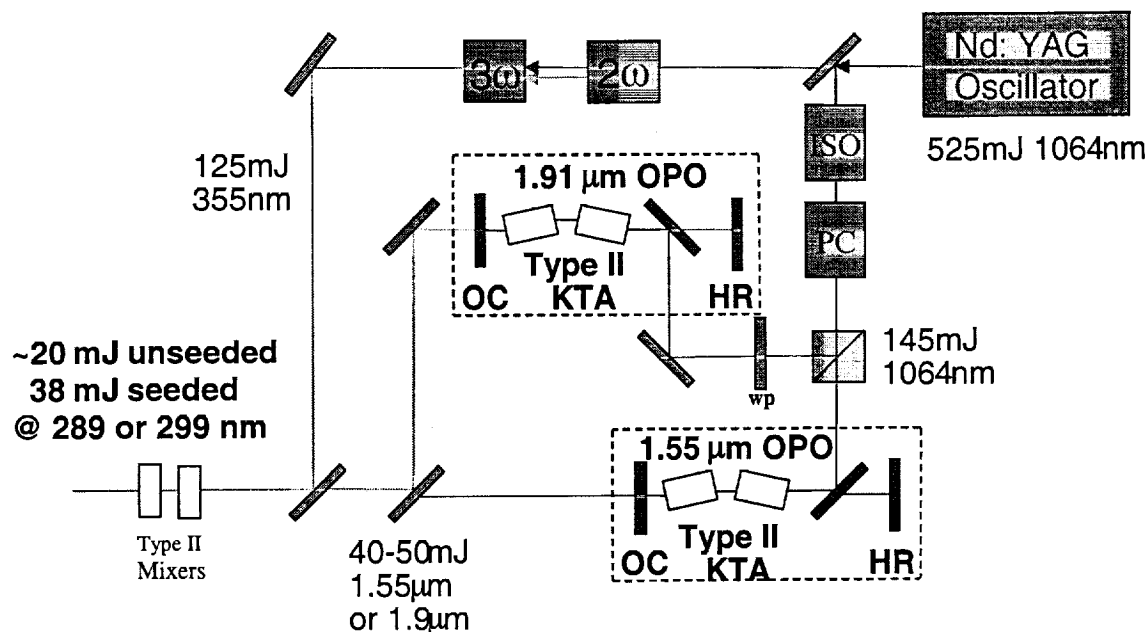


Figure 3: All-solid state tunable frequency-mixed Type II KTA OPO

4. TELESCOPE RECEIVER

The lidar receiver utilizes a 12" square parabolic primary mirror (Figure 2) and a grating-based spectrometer as a wavelength filter. An optical layout of the receiver system is shown in Figure 4. Daylight prefiltering is performed by reflective dielectric coatings on the fold mirrors before the grating. The +1 and -1 orders of the grating provide the far and near field channels, respectively. With commercially available dielectric coatings, the throughput efficiency from the atmosphere to the detector plane is calculated to be ~60% for the far field (analog and photon-counting mode) channel. The near-field (analog-mode) channel utilizes the negative first order reflection from the grating and does not reduce the efficiency of the far-field channel.

Due to the anamorphic properties of the grating, the image of the field stop in the focal plane of the grating is an ellipse with a major diameter equal to 1.5 mm. A field mask is placed in the focal plane with four elliptical apertures centered at the locations of the on-line and off-line wavelengths for the near and far field channels. For stock commercial triplet lenses and gratings, the bandpass in the focal plane of the grating is computed using a commercial raytracing program to be 2.6 nm (FWHM) for a single wavelength channel. We have tested this calculation in the laboratory with a custom collimated light source consisting of a fiber-coupled white light source and a 16" collimating telescope assembly. This system fills the receiver primary mirror with a collimated beam containing both uv and visible components. A fiber which is coupled to a uv spectrometer is translated across the aperture behind the field mask. The measured bandpass has a FWHM equal to 2.4 nm, in excellent agreement with the result from the raytracing program. By opening a shutter in the focal plane of the grating to allow through only the transmitted wavelength, the bandwidth can be maintained at 2.4 nm for a multi-wavelength system.

A fast-shutter device known as a membrane mirror light shutter (MMLS) has been tested to address the problem of detector saturation and signal-induced bias due to the strong near field return. A MMLS consists of a substrate that supports a 2-D array of wells that are etched into an insulating layer atop the substrate. A thin aluminum-coated membrane-mirror bonded to the insulating layer covers the wells. An electrode located at the base of the wells allows voltages to be applied across the wells in order to electrostatically deform the membrane mirror into the wells. When no voltage is applied the MMLS is simply a flat mirror. When a voltage is applied the mirror essentially becomes a 2-D diffraction grating with a period

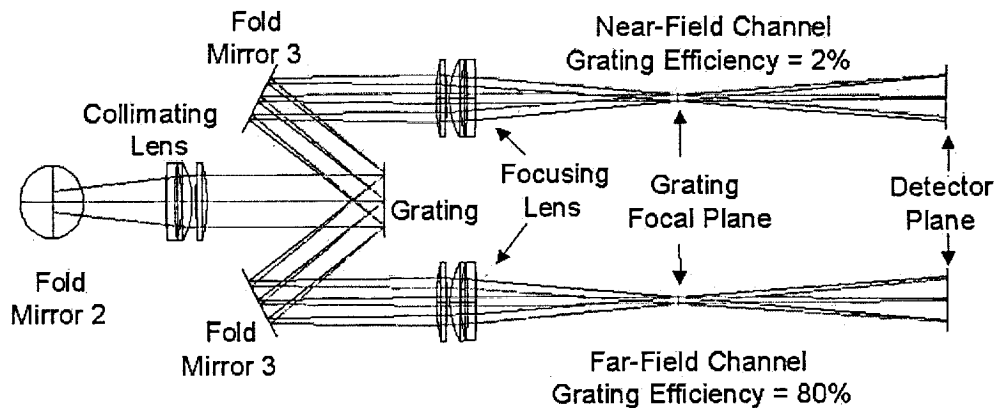


Figure 4: Optical setup of the receiver.

determined by the spacing of the wells. A lens is placed after the MMLS to focus the light down to an aperture and the grating mode diffracts the light out of the aperture when the voltage is applied. As a result, the MMLS acts as an optical shutter with switching times which can be under $1\mu\text{s}$. The membrane is enclosed in a housing with an antireflection-coated window to maintain a vacuum environment. The entire unit fits into a standard mirror mount for 2-inch optics.

By replacing a fold mirror #3 (see Figure 4) with the MMLS, we can create a fast optical shutter by diffracting the light out of the focal plane aperture. This shutter will block the optical scatter and very near-field return that causes the signal-induced-noise (SIN) problem with photomultiplier tubes, thus eliminating a serious source of error in current DIAL systems. Alternatively, the device could be used as a programmable attenuator to correct for the R^2 dependence of the lidar return.

In order to utilize an MMLS in our system, a custom unit with a large active area and optimized for uv operation was purchased. The custom device has a 50mm active area and a 12.1 nf capacitance. Extinction was measured to be 1000:1 at 632 nm. Since the capacitance of this device is ten times greater than for the standard units, switching times with the standard factory electronics has been measured to be 14 microseconds. Electronics are currently on order which have demonstrated submicrosecond switching times with a 12 nf dummy load.

The detectors chosen for the near and far field channels are Hamamatsu 7400P-06 series minipmt's. Compared to standard photomultiplier tubes, these detectors are very compact, operate at room temperature, are linear over 6-7 orders of magnitude, have sub-nanosecond rise times and very good signal-induced-noise characteristics. However, their quantum efficiencies are less than standard tubes, their gains are less, their excess noise factors are somewhat higher, their active areas are much smaller, and they cannot be gated.

5. SIMULATED SYSTEM PERFORMANCE

We have calculated the expected performance for our system using an actual ozonesonde data set and the receiver, transmitter, and data acquisition characteristics listed in Table 1. The signal to noise (S/N) ratio for the simulated DIAL return signals are calculated incorporating the contributions of several error sources: signal noise, sky background (30° zenith angle), dark current/counts of the PMT, A/D resolution, and dead time error. A S/N ratio of better than 10:1 can typically be obtained in about 30 min and with only a few minutes averaging time for altitudes greater than 10 km and lower than 3 km, respectively. Measurements into the stratosphere are possible with this S/N with the far-field photon-counting channel. By choosing wavelengths optimized for the stratosphere, the S/N in this region can be improved. These calculations have been discussed in greater detail elsewhere.^{2,3,5}

Transmitter	
Pulse Power, on/off-line	20 / 10 mJ
Repetition rate	20 Hz, single wavelength pulses
Wavelength, on/off-line	290 / 300 nm
Receiver	
Telescope area	12" squared
Bandwidth for each wavelength	2.6 nm
Receiver transmission near / far field	1.6 % / 65 %
Field of View	1 mrad full angle
PMT	Standard specifications Of Hamamatsu H7400 series mini tubes, for example, QE=18%, noise excess factor ~ 1.55
Photo counting dead time	3.3ns (5% error assumed) (300 MHz counter, 3x PMT rise time = 1.8ns)
Atmosphere	
Laser light extinction (Lidar equation)	Rayleigh and ozone extinction; Aerosol extinction included in planetary boundary layer (PBL) depending on location
Sampling	
Time averaging	30 min
Range bins, near/far field channel	300 / 1000 m

Table 1: System and integration parameters used for DIAL performance simulations.

6. DATA ACQUISITION AND CONTROL

The data acquisition and control hardware is integrated in a rack-mounted industrial PC. The analog and photon counting channels utilize a Gage scope card ISA1012 and a photon counting scaler card MCS100 by Santa Fe Energy Research. A Multi-function I/O card (National Instruments, PCI6110E) is used for digital and analog control signals and timing. LabVIEW software provides a user-friendly graphical interface for instrument control, data acquisition, and online processing and display.

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